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Ground Modifications by a Combination of Dynamic Compaction, Consolidation, and Replacement

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GROUND MODIFICATION BY A COMBINATION OF DYNAMIC COMPACTION, CONSOLIDATION, AND REPLACEMENT

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ABSTRACT

Modification of weak soils can be accomplished by dropping a heavy weight onto a ground surface. The mechanisms for improving the ground by this technology can be described as dynamic compaction, dynamic consolidation, or dynamic replacement. The importance of each mechanism at one site is dependent on soil conditions, impact energy, weight dimensions, etc. A case study presented herein demonstrates how each mechanism affects the treatment effectiveness of this technology. The selected site has a mix of cohesive and cohesionless soil layers. A pilot study was conducted before the construction program for the whole site. Evaluation of the treated ground by laboratory testing and in-situ testing indicated the improvement of soil properties.

KEYWORDS

Dynamic compaction, dynamic consolidation, dynamic replacement, ground modification, impact.

INTRODUCTION

Dropping a heavy weight from a certain height onto a ground surface has been proved to be able to effectively improve the properties of soils in most applications. The effectiveness of this technology depends on composition of soils, ground water table, impact energy, size of weight, etc. For cohesionless soils, since rearrangement of soil particles is possible and excess pore water pressures can dissipate quickly, they can be easily densified by applying external energy. For unsaturated soils, the mechanism of densification is the same as that for the Proctor compaction in the laboratory (Mitchell, 1981). Densification of cohesionless and unsaturated soils is normally referred to as dynamic compaction. Heavy tamping has also been used for saturated cohesive soils in the world. However, the mechanism of modification of cohesive soils is totally different from that of cohesionless or unsaturated soils. Dynamic consolidation theory was proposed by Menard (1974) to explain why the heavy tamping technique can work for cohesive soil. Dissipation of excess pore water pressures is the major issue for this application. In addition, heavy tamping has been adopted to form granular material columns in soft clay by creating a large diameter hole, filling granular materials in, and then compacting them. This technique is termed as dynamic replacement, or dynamic replacement and mixing, or dynamically-compacted gravel column (Lee, et al., 1985; Broms, 1987; Guo, et al. 1993). Eight to nine-meter long granular material columns were reported by Guo, et al. (1993). The granular materials vary from sand, gravel to coarse aggregate.

A case study presented herein will demonstrate ground modification of a container storage site by a combination of dynamic compaction, dynamic consolidation, and dynamic replacement.

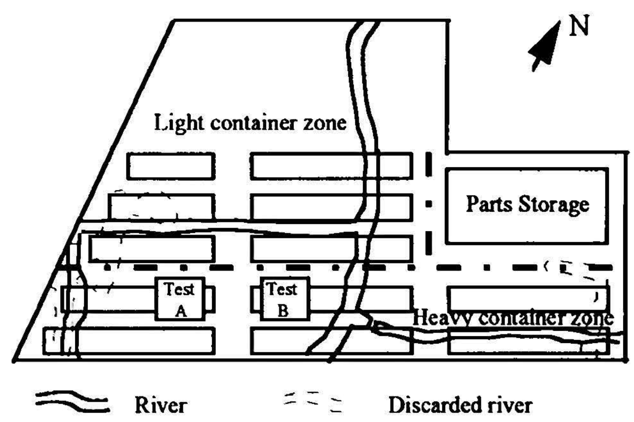


Fig. 1 Layout of the site

Table 1 Physical and mechanical properties of soils

No	Soil Classification	H (m)	w (%)	γ (kN/m^3)	e	I_p	c (kPa)	ϕ (^{0})	N	P_s (MPa)	q_a (kPa)
1	Fill (CL)	0.5									
2	Silty clay (CL)	2.0	32	18.8	0.92	15	14	14.2	5	0.79	100
3	Silty clay (OL)	1.0	42	17.7	1.20	16	8	11.4	1	0.53	75
4	Sandy silt (ML)	4.0	30	18.	0.88	-	5	26.5	9	3.36	130
5	Clay (OL)	12.0	50	17.2	1.40	20	8	7.1	1	0.54	65
6	Silty clay (CL)		25	19.8	0.72	16	35	10.5		2.01	95

w = moisture content; γ = unit weight; e = void ratio; I_p = plasticity index; c = cohesion; ϕ = friction angle; N = SPT blow count; P_s = total cone resistance; q_a = allowable bearing capacity.

SITE AND SOIL CONDITIONS

The container storage site is located in Shanghai, P. R. China. Survey and Geotechnical reports showed that there existed several active and discarded rivers across the site as shown in Fig. 1. The active rivers were filled with a mixed fill comprising of crushed stone, sand, and very few fine grain soils prior to construction. Based on the service purpose, the site can be mainly divided into three zones: heavy container, light container, and parts storage. The required allowable bearing capacity for the heavy container zone is 170 kPa, which exceeded the allowable bearing capacity of the native soils. Therefore, modification of the weak soils within the heavy container zone was needed. Physical and mechanical properties of soils at this site are listed in Table 1. The ground water table was 0.5 meter below the original grade. Prior to the construction for the whole heavy container zone, two areas as shown in Fig. 1 were selected for a pilot study to verify the effectiveness of this technique.

PILOT STUDY

Fills and Drainage Path

Test A and B zones have different configurations of fill materials and drainage path as shown in Fig. 2. The purpose to place fills on the original grade is to form a workable surface for construction equipment like cranes, to increase the distance to the ground water table, to reduce excessive weight penetration depth and ground heave. Wick drains in Test B zone were adopted to speed up the dissipation rate of excess pore water pressures. Ditches were excavated at both zones with 1.0 m wide and 1.5 m deep around. The area of each test zone is 35x35 m^2.

Tamping Program

For both zones, tamping was conducted in a 3.5 m by 3.5 m grid. The impact energy for each drop was 2100 kN-m at primary, secondary, and tertiary locations, while the impact energy during the ironing phase was 1000 kN-m per drop and number of drops on each point with a 14.2 t weight was 3. In Test A zone, a 14.2 t weight with a diameter of 2.35 m was used and dropped from a height of 15.3 m. Primary, secondary, and tertiary drop points each received 9 drops. In Test B zone, primary and tertiary points received 10 and 8 drops, respectively, of the 14.2 t weight dropping from 15.3 m while secondary drop points received 8 drops of a 16 t weight with a diameter of 2.1 m dropping from 13.5 m.

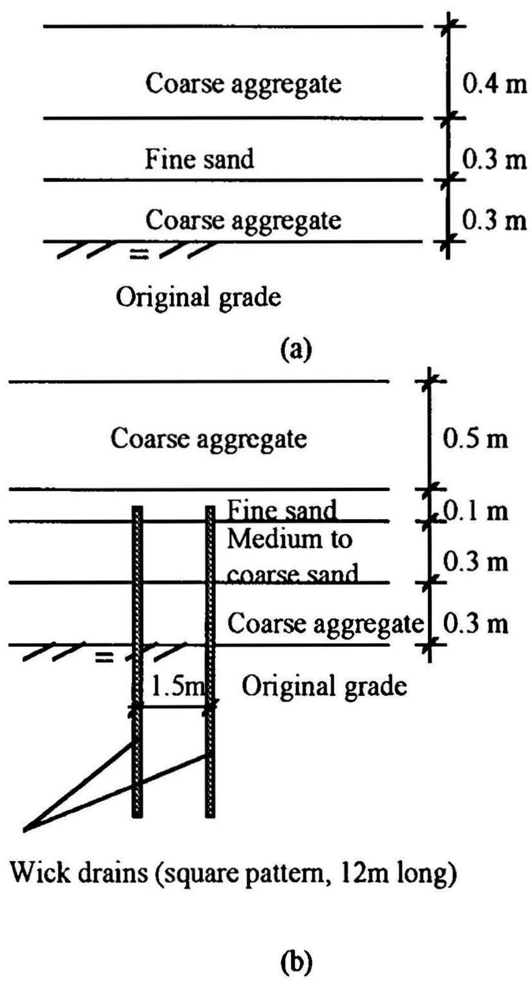
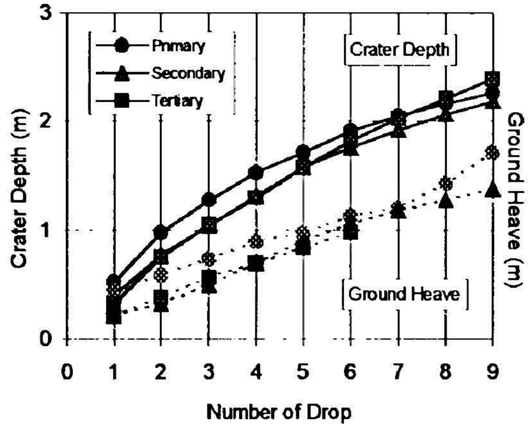
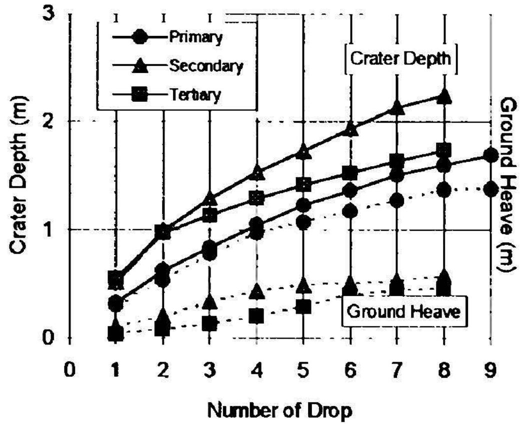


Fig. 2 Fill materials and drainage paths



(a) Test A



(b) Test B

Fig. 3 Crater Depth and Ground Heave versus Number of Drop

Crater Depth and Ground heave

As shown in Fig. 3, the crater depth in Test A zone is slightly larger than that in Test B zone, while the ground heave in Test A zone is much larger than that in Test B zone. This means that more applied energy was absorbed in Test B zone than in Test A zone. The difference results from different configurations of fill materials and drainage paths in these two test zones. In Test B, the secondary compaction induced relatively large crater depth since a heavier and smaller diameter weight was used. Therefore, this is a good condition for dynamic replacement.

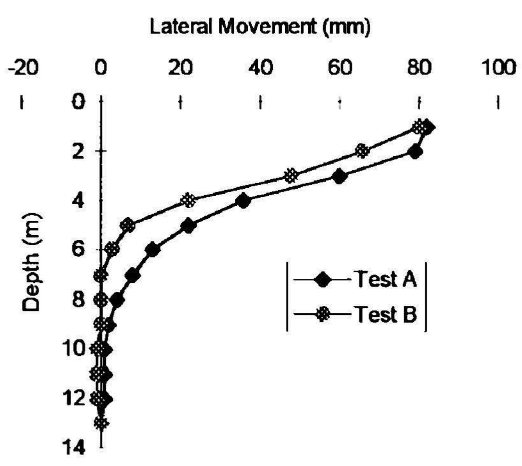


Fig. 4 Soil Lateral movement around Test Zones

Soil Lateral Movement

The soil lateral movement in two test zones was monitored using inclinometers. As shown in Fig. 4, the soil lateral movement around Test A zone is larger than that around Test B zone. Due to the same reason as discussed above, the energy loss in Test A zone is larger than that in Test B zone. Based on the results in Fig. 4, the influence depth for Test A zone is around 7 ft., while the influence depth for Test B zone is around 9 ft.

Dissipation of Pore Water Pressure

The dissipation rates of excess pore water pressures after tamping in both test zones are compared in Table 2. The existence of wick drains in Test B zone had accelerated the dissipation of excess pore water pressures. This is a good condition for dynamic consolidation.

GROUND MODIFICATION WORK

Based on the pilot study, the effectiveness of heavy tamping depended on the configuration of fill materials, the drainage paths, the dimension of weight, and the tamping program. A 0.3 m thick mixed granular material layer followed by a 0.4 m thick medium-coarse sand layer and a 0.3 m thick aggregate layer was selected. The gradation of the mixed granular material is as follows:

Grain size (mm)	% weight
38 to 65	20
25 to 38	30
13 to 25	30
0 to 13	20

The same impact energy (2100 kN-m/per drop) was selected for the construction of the whole site. As indicated in the pilot study, the heavy weight (16 t) with a relatively low drop

Table 2 Dissipation rate of excess pore water pressures in Test A and B zones

Phase	Test A			Test B		
	Δu_i (kPa)	Δu_t (kPa)	$(\Delta u_i-\Delta u_t)/\Delta u_i$	Δu_i (kPa)	Δu_t (kPa)	$(\Delta u_i-\Delta u_t)/\Delta u_i$
Primary	48	13	0.73	42	10	0.76
Secondary	22	9	0.59	43	9	0.79
Tertiary	41	18	0.56	24	8	0.67

Δu_i= initial excess pore water pressure right after compaction; Δu_t excess pore water pressure two days after compaction.

height (13.5 m) could induce deeper craters and less ground heave than the relatively light weight (14.2 t) with a high drop height (15.3 m). Therefore, the 16 t weight with the 13.5 m drop height was adopted for the primary and the secondary tamping. Considering the strength of the soil would temporarily decrease after the primary and secondary tamping, a light weight (14.2 t) with a high drop height (15.3) and a large weight base was used for the tertiary tamping.

As shown in Fig. 3 (b), the crater depth did not change too much after the number of tamping at the same location reached 7. Therefore, this number was chosen to guide the construction. However, additional tamping was required when the increase of the crater depth at the last drop was larger than 0.1 m. Based on the observation during the construction, the crater depth varied from 1.00 to 2.20 m. All craters were filled with the fill materials to form granular columns.

EVALUATION OF IMPROVED GROUND

Laboratory Test

Soil sampling and laboratory testing were performed more than 28 days after the completion of the modification work for evaluating the physical and mechanical properties of treated soils. The comparison of the properties of soils before and after treatment is summarized in Table 3. Since the thickness of the third layer is very thin at some locations, no sample was taken. It is shown that the properties of the second and the fourth soil layers have been obviously changed after the modification, while the change of soil properties for the fifth layer is minor. No significant change of soil properties for the fifth layer is attributed to the location of this layer beyond the influence depth as discussed above.

In-Situ Test

In addition to laboratory tests, three types of in-situ tests, SPT, CPT, and loading test, were also conducted at the same site. The comparison of SPT and CPT results is tabulated in Table 4. Similar as the results from the laboratory tests, the second and the forth layers have significant increase of soil strength. It is clear that the increase of soil strength for the second and the fifth layers (cohesive soil) is due to dynamic consolidation, while the increase of soil strength for the forth layer (cohesionless soil) is due to dynamic compaction.

The results from six loading tests on the treated ground are shown in Fig. 5. Based on the criteria for determining allowable bearing capacity of a foundation soil commonly used in China, i.e. the allowable bearing capacity equal to the bearing pressure at s/b=0.2 (s=settlement, b=plate with), the allowable bearing capacity of the treated ground from Test T1 to Test T5 is more than 250 kPa. However, the test result from Test T6 had much lower allowable bearing capacity (approximately 130 kPa) than others. The reason for this

Table 3 Comparison of physical and mechanical properties of soils before and after modification

Soil Layer		w (%)		γ		e		I_p		ϕ		c		q_a	
No	Class.	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
2	CL	32.1	26.6	18.8	19.3	0.92	0.77	15.0	14.0	14.0	21.5	14	16	100	150
4	ML	30.8	30.1	18.2	18.9	0.88	0.88	-	-	26.5	27.8	5	12.4	130	170
5	OL	50.1	50.7	17.2	17.2	1.40	1.41	20.3	21.6	7.1	14.3	8	6.8	65	70

w moisture content; γ unit weight; e void ratio; I_p = plasticity index; c cohesion; ϕ friction angle; q_a = allowable bearing capacity.

Table 4 Comparison of SPT and CPT results before and after modification

Soil Layer		N (blow/300mm)		P_s (MPa)	
No	Classification	Before	After	Before	After
2	CL	5	8	0.79	3.15
4	ML	9	15	3.36	5.15
5	OL	1	2	0.54	0.68

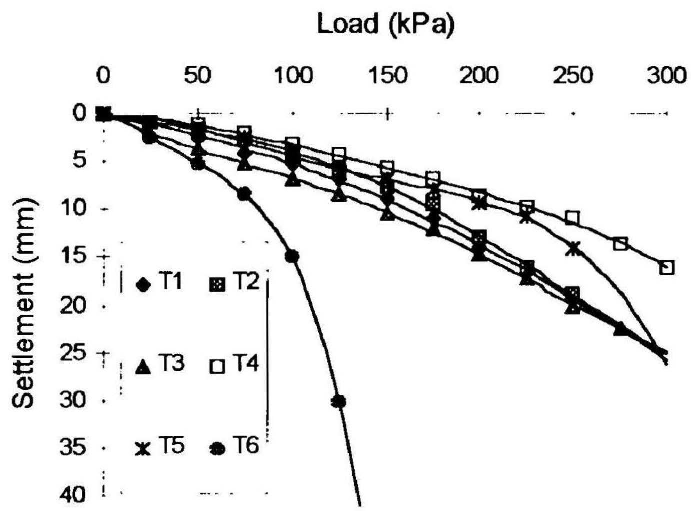


Fig. 5 Plate Loading Tests on the Treated Ground

low bearing capacity is due to the location of this test. The loading plate for Test T6 was placed between drop points, while all the other tests were located on drop points. As mentioned earlier, the craters at this site have depths ranging from 1.00 to 2.20 m, which were filled with fill materials to form granular columns. The mechanism for this treatment can be considered as dynamic replacement. Due to the difference in bearing capacity at the drop points and between the drop points, a formula is proposed below to estimate the allowable bearing capacity for the treated ground:

$$\overline{q}_a = q_{as}(1 - a_s) + q_{ac}a_s \tag{1}$$

where $\overline{q}_a$ = the overall allowable bearing capacity of the treated ground;

q_{as} = the allowable bearing capacity of the soils between the drop points;

q_{ac} = the allowable bearing capacity of the compacted columns at the drop points;

a_s = the area ratio of the compacted columns within the entire treated area.

Based on the results obtained from the loading tests, the overall allowable bearing capacity for the treated ground is 193 kPa, which is larger than the required allowable bearing capacity.

SUMMARY & CONCLUSIONS

This case study has showed that heavy tamping is a ground modification technology which can improve a weak ground by a combination of mechanisms - dynamic compaction, dynamic consolidation, and dynamic replacement. Selecting appropriate configuration of fill materials and drainage paths and weight dimensions can increase the effectiveness of this technology. For cohesionless or unsaturated soils, dynamic compaction is a controlling mechanism. For saturated clays, dynamic consolidation and dynamic replacement are two major mechanisms. Dynamic replacement will be more effective when a relatively heavy and small diameter weight is adopted. Dynamic replacement does not require the dissipation of excess pore pressures while dynamic consolidation does.

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